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Numerical simulation and experimental study of infrared suppression of diesel engine exhaust gas under water

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Abstract: [**Objectives**] To reduce the thermal wake of submarine during snorkeling, [**Methods**] a two-stage cooling method is proposed, which can suppress the infrared radiation of high-temperature exhaust gas under water; and then the water surface temperature fields before and after infrared suppression are analyzed on the basis of the finite element fluid analysis method; and finally, an underwater exhaust gas experiment platform is built on the basis of the preliminary data obtained by simulation, so as to test the infrared radiation brightness of water surface and the temperature of underwater section before and after infrared suppression. [**Results**] The results show that the two-stage cooling measure has an excellent infrared suppression effect on the high-temperature exhaust gas of diesel engine, and the maximum infrared brightness of the water surface can be reduced by 90%. [**Conclusions**] This method has a good engineering application value and military significance for the improvement of submarine's concealment.

Key words: diesel engine; exhaust gas under water; infrared signature suppression; test

CLC number: U674.7+03.8

0 Introduction

In the design of modern ships, stealth performance has received more and more attention. A series of studies have been carried out all over the world in terms of infrared suppression measures for diesel engine exhaust gas of surface ships, and some infrared suppression technologies have been applied to various types of ships [1-6]. However, the submarine needs to float out to charge in the snorkeling state. At this time, the exhaust port of diesel engine is close to the water surface; the exhaust temperature is high; and the flow rate is large. It is easy to form a wide range of temperature difference on the sea surface and be detected by infrared detection equipment. Although many scholars have studied infrared suppression technology of submarine diesel engine, it is still in the preliminary research stage [7-12].

In this paper, two-stage cooling measures will be designed for the problem of excessive flue-gas temperature in the exhaust manifold. First, a water mist spray system is built in the exhaust manifold to pre-cool the high-temperature flue gas using the latent heat of vaporization of water. Second, through the small holes at the end of the exhaust manifold, a large amount of flue gas is dispersed and discharged, and the heat exchange between the gas and the seawater is increased, so that the temperature of the flue gas is diffused into the seawater as far as possible. In order to verify the correctness of the design, the simulation model is established and the calculation is carried out. Then, the underwater exhaust gas system model of diesel engine is built according to the calculation results, and the infrared imager and thermometer are used to measure the surface infrared, underwater temperature, exhaust-pipe back pressure and other data under different conditions.

1 Modelling and simulation

The physical model parameters of diesel engine exhaust are as follows: the nozzle diameter is 100 mm, the high-temperature gas velocity is 10 m/s, and the gas temperature is 350 °C (the gas in this paper is approximately treated as air); the nozzle is placed

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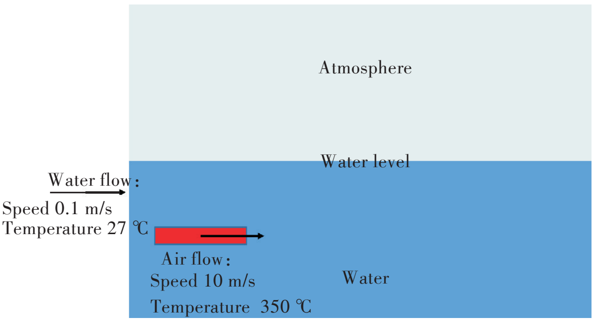
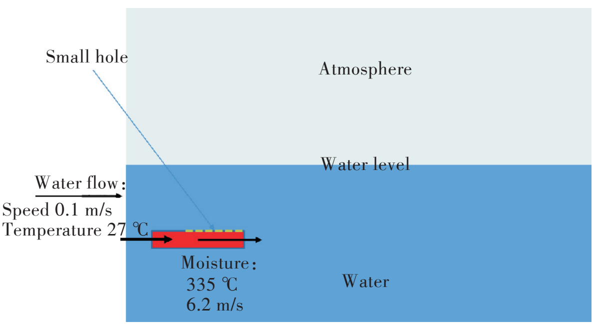
0.5 m below the water surface, the water flow rate is 0.1 m/s, the water temperature is 27 ℃, and the water flow direction is consistent with the air injection direction. The simulated surface temperature distribution is shown in Fig. 1.



(a) Built-in spray exhaust gas model



(b) Built-in spray+end small-hole exhaust model

Fig.1 The model of diesel engine under water

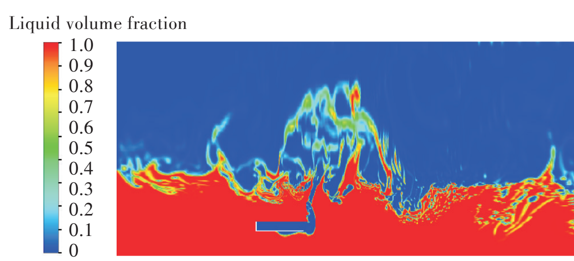
For the model shown in Fig. 1 (b), the cooling effect of the spray device inside the exhaust pipe on the high-temperature flue gas is firstly simulated. In the process of simulation, the nozzle flow rate is changed from 0.01 to 0.03 kg/s, and the average particle size of mist spray is 30 and 50 μm. Table 1 shows the average temperature of different outlet surfaces of exhaust pipes obtained by simulation. From the simulation results, it can be seen that when the nozzle flow rate is 0.03 kg/s, the high-temperature airflow of 350 °C can be cooled to about 60 °C.

Table 1 The outlet temperature with different flow rates and particle diameters

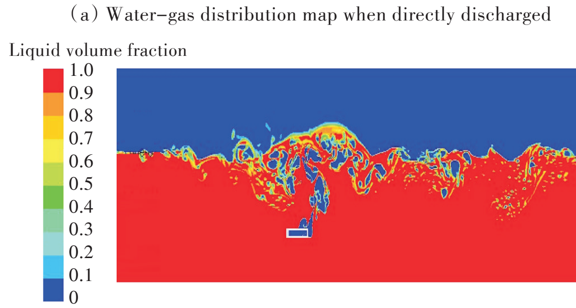
Nozzle flow rate /($kg \cdot s^{-1}$)	Average particle size of nozzle /μm	Exhaust gas temperature /℃
0.01	50	199
0.02	50	81
0.03	50	62
0.01	30	199
0.02	30	73
0.03	30	59

In the case where the nozzle flow rate is sufficient, the latent heat of vaporization can be fully utilized and the exhaust gas temperature can be greatly reduced. The smaller particle diameter leads to easier evaporation, which has a positive effect on the cooling effect. It can be seen from the simulation that the high-temperature airflow in the pipe is cooled by the water spray. When the flow rate is reduced from 10 m/s of the inlet to 6.27 m/s of the outlet, and the temperature is lowered from 350 ℃ of the inlet to about 60 °C of the outlet, the relative humidity at the outlet section is about 100%. Through the process of mist spray cooling, the high-temperature airflow turns into moisture flow. Therefore, the nozzle flow rate can be selected as 0.03 kg/s through the above simulation. The smaller average particle size of mist spray results in the better cooling effect, but the smaller particle size leads to the higher requirement of booster pump in engineering application. Moreover, through simulation comparison, under the flow rate of 0.03 kg/s, 30 μm and 50 μm particle sizes have the same cooling effect, so the particle size of mist spray is selected as 50 μm. Fig. 2 shows the simulation comparison diagram of diesel engine exhaust gas under water when directly discharged and after infrared suppression.

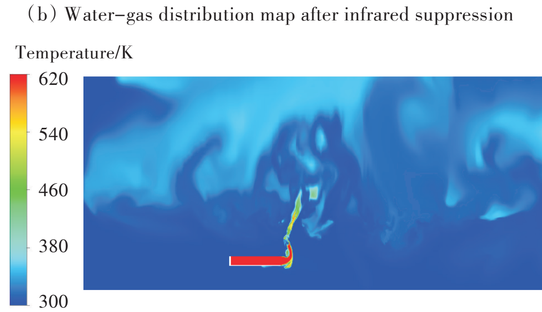
From the simulation results shown in Fig. 2, it can be known that if the underwater exhaust gas is not controlled, the high-temperature exhaust gas is easy to rise to the water surface and emit into the air. Af-



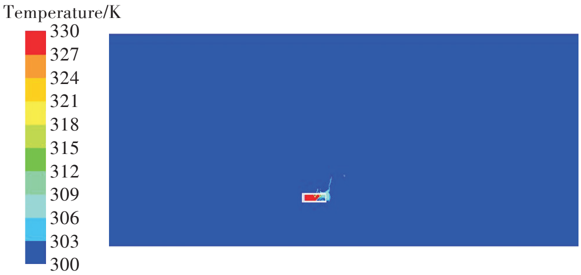
(a) Water-gas distribution map when directly discharged



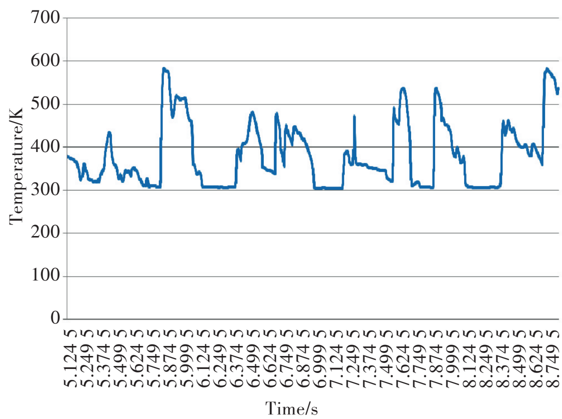
(b) Water-gas distribution map after infrared suppression



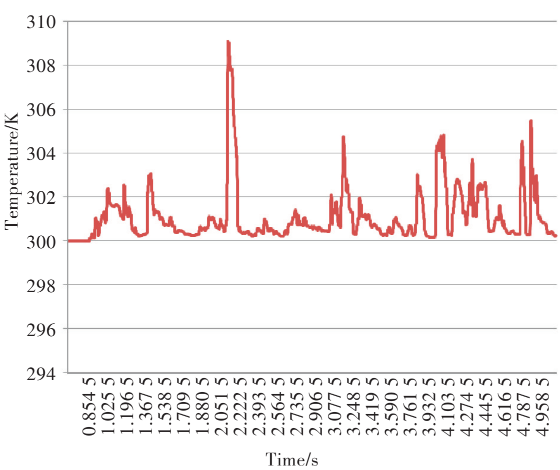
(c) Temperature contours when directly discharged



(d) Temperature contours after infrared suppression



(e) Time history map of highest temperature of water level when directly discharged



(f) Time history map of the highest temperature of water level after infrared suppression

Fig.2 The comparison of simulation results when diesel engine exhaust under water on different conditions

ter the infrared suppression, the temperature of the exhaust manifold is relatively high, while the temperature of other parts is basically kept in a stable state. Underwater exhaust gas will cause waves on the water surface, which cannot be kept horizontal. To unify the measurement standard, through setting the monitoring of water level temperature, the maximum temperature of the water level can be reduced by about 300 ℃ after the infrared suppression, which is basically close to the original ambient temperature. The simulation results show that the infrared suppression device can greatly improve the infrared radiation of underwater exhaust gas.

2 Test system

According to the simulation results, the test system shown in Fig. 3 is designed. The test device consists of circulating water flume, circulating water pump, simulator of diesel engine exhaust gas, exhaust pipe shunt device, underwater exhaust pipe, flow regulating valve, and infrared suppressing device (spray system and small-hole exhaust device). The diesel engine simulator emits high temperature gas at specified temperature. The gas flows into a three-way valve and is divided into two directions. At one end, it is discharged to the underwater exhaust manifold, and it is discharged to the atmosphere at the other end. By adjusting the size of the exhaust valve, we can make the underwater exhaust gas flow reach the specified value. A water mist spray device is built in the underwater exhaust manifold, which is controlled by a special jet pump to achieve the set flow rate. To simulate the underwater movement of the submarine, we use the circulating water pump in the water tank to enable the water to have a certain flow rate in the water tank.

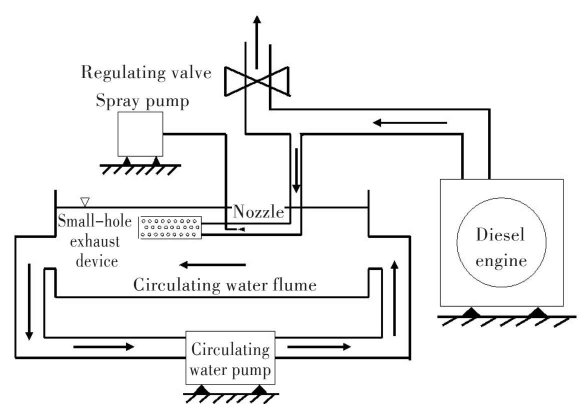


Fig.3 Schematic diagram of experiment scheme

The test parameters are consistent with the previous simulation model parameters as follows:

1) Relative flow velocity: 0.2 m/s;

2) Temperature of water: 27.3 °C;

3) Diameter of diesel exhaust nozzle: 100 mm;

4) Speed and temperature of diesel engine exhaust gas: 10 m/s, 350 °C;

5) Distance of the center of diesel exhaust pipe from the depth of water: 0.5 m;

6) The parameter requirements of built-in nozzle: the water pressure: 7.5 kg/cm^2; flow rate: 0.03 kg/s;

7) Design parameters of small holes at the end of exhaust pipe: 2 400 small holes with a diameter of 2 mm.

The general diagram of the experiment setup is shown in Fig. 4.

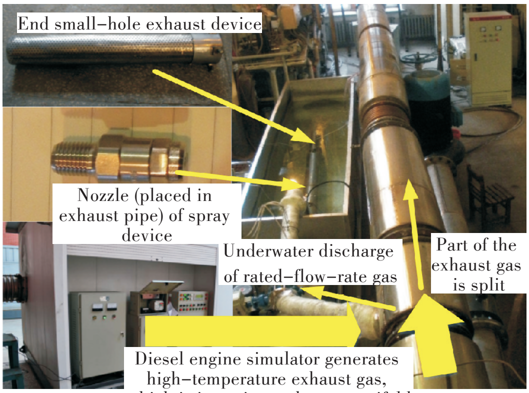


Fig.4 The experiment setup

3 Test equipment

Since the diesel engine has high requirements for back pressure, in order to verify that the infrared suppression device has no effect on the normal operation of the diesel engine, we set pressure sensors in the exhaust manifold to detect changes in back pressure in various states. The Agilent temperature measurement system adopted has two measuring points in the exhaust pipe: one is in front of the nozzle inside the exhaust pipe; the other is behind the nozzle inside the exhaust pipe. The first temperature sensor is mainly used to monitor whether the input gas temperature is within the rated value, and the latter one is used to detect the temperature change of the exhaust gas after the latent heat of vaporization works. At the same time, the infrared measurement system is used as the means of infrared monitoring of water surface. Considering the high temperature of the measured object, the infrared measurement system adopts the medium-wave Image IR 8325 thermal imager, as shown in Fig. 5.


Fig.5 The infrared data record system

4 Test results and analysis

In order to verify the effect of the two-stage cooling system on the back pressure of diesel engine, we measure the pipe pressure in the following four states. The results are shown in Table 2.

When the spray device inside the exhaust pipe is turned on, the back pressure in the state of the ordinary exhaust pipe and the small-hole pipe is lowered to some extent, because the volume of the gas becomes smaller after being cooled, but the change is not obvious. In the state of the ordinary exhaust pipe and the small-hole pipe, although the opening area of the latter is larger than that of the former, the small hole has additional resistance loss. Besides, according to observation, some of the small holes are not involved in underwater exhaust. Small-hole exhaust will increase the resistance loss to a certain extent, but if the opening is designed reasonably and the proportion of increase is small, there is almost no influence on the back pressure.

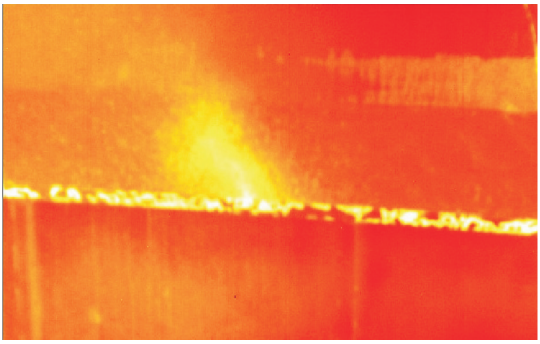
Table 2 The pressure in the exhaust pipe under different conditions

Exhaust pipe state	Spray state	Exhaust gas temperature/℃	Pressure /kPa
Ordinary exhaust pipe	Off	350	4.79
Ordinary exhaust pipe	On	350	4.73
Small-hold pipe	Off	350	5.17
Small-hold pipe	On	350	5.05

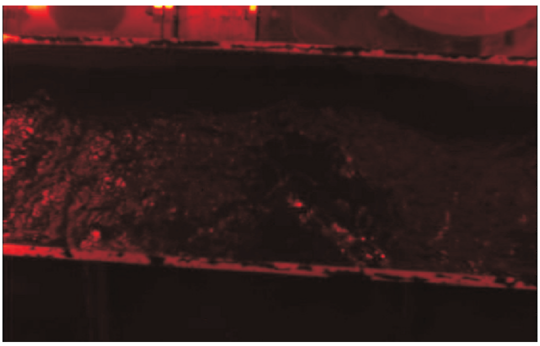
In order to analyze the infrared suppression effect of the two-stage infrared cooling system, we collect the infrared radiation intensity of the water surface in the water tank under two working conditions: 1) The high-temperature exhaust gas of the diesel engine is directly discharged into the water (conventional exhaust); 2) the high-temperature exhaust gas of the diesel engine is discharged to water after two-stage cooling (infrared suppression). The infrared thermal images of the water surface under these two conditions are shown in Fig. 6.

Comparing Fig. 6 (a) and Fig. 6 (b), we can find that the infrared radiation in Fig. 6 (a) is very strong, and the hot air floats directly to the water surface in the form of much gas under water, causing the higher spray of water on the surface. In Fig. 6 (b), because the small hole can divide exhaust gas into several small airflows, which reduces the floating speed and increases the heat exchange, the water situation is relatively moderate, and the infrared characteristics of the water surface are basically eliminated. The high temperature parts in Fig. 6 (a) and Fig. 6 (b) are extracted and subjected to infrared analysis, and the infrared radiation brightness before and after infrared suppression is obtained as shown in Table 3.

The results shown in Table 3 show that after two-stage cooling of high-temperature exhaust gas, the radiation brightness of 3–5 μm decreases greatly; the maximum radiation brightness decreases from 50.85 W/m^2 to 6.02 W/m^2; the average radiation



(a) Infrared test results under conventional exhasut



(b) Infrared test results after infrared suppression

Fig.6 High temperature exhaust infrared image in the tank before and after infrared signature suppression

Table 3 Comparison of infrared radiation brightness of water surface under different conditions

Exhaust gas state	3–5 μm maximum radiation brightness /(W·m^{-2})	3–5 μm average radiation brightness/ (W·m^{-2})
Ordinary exhaust pepe	50.85	17.36
Two-satge cooling	6.02	5.86

brightness decreases from 17.36 W/m^2 to 5.86 W/m^2; and the maximum radiation brightness is reduced by about 90%, which achieves the purpose of suppressing the strong infrared radiation source. Under the two-stage cooling effect, the maximum radiation brightness is basically equal to the average radiation brightness, indicating that there is no obvious infrared "bright spot" in the water surface after infrared suppression.

In order to further prove the cooling effect of built-in spray device and small-hole exhaust device, we install a temperature sensor array above the exhaust pipe in the pool. It has a total of three rows, and eight sensors are arranged in each row, as shown in Fig. 7. The underwater temperatures in the following three states are measured separately:

1) State 1: The built-in spray system is turned on, and the diesel engine exhaust gas is cooled by two-stage cooling in spray and small hole;

2) State 2: The built-in spray system is turned off, and infrared suppression is performed only through the small-hole exhaust device;

3) State 3: The built-in spray system is turned off; the small-hole exhaust pipe is removed; and the hot air is discharged directly under water.

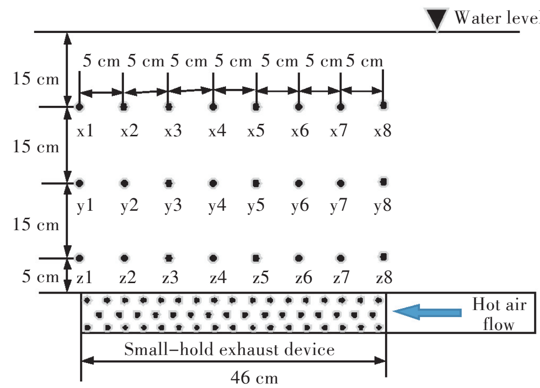
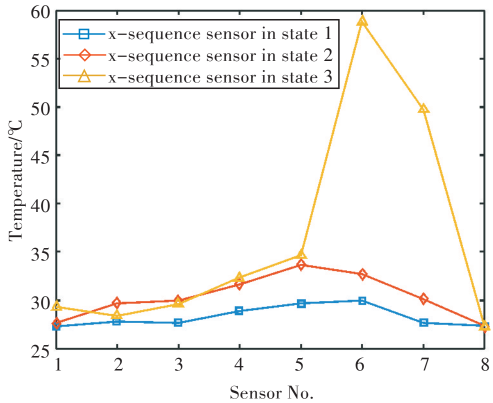


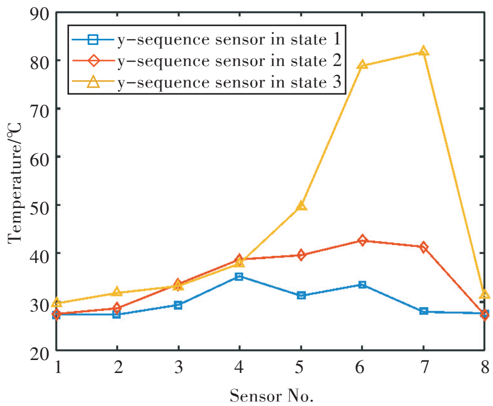
Fig.7 The location of temperature sensor

Comparing the three figures in Fig. 8, we can see that although the small holes are evenly arranged, it is obvious that in states 1 and 2, the high temperature of the x, y, z sequence sensors is concentrated in the front section of the exhaust pipe (near the exhaust port end) and the middle section, and the rear section (away from the exhaust port end) is usually cooler. This is because when the small-hole exhaust device discharges gas, most of the gas is discharged from the small holes in the front section, and less gas flows through the small holes in the rear section. As can be seen from Fig. 8 (a), the temperature near the water surface decreases significantly after the installation of small-hole exhaust device and built-in spray system, and the average temperature is about 28.6 °C, which is close to the ambient water temperature of 27.3 °C. In the case of no built-in spray system, although the temperature is also significantly reduced, it is still about 5 °C higher than the ambient temperature, so that relatively strong local infrared radiation can still be formed on the water surface. When the high-temperature gas is directly discharged from the exhaust pipe without any infrared control measures, a strong heat source is formed near the water surface, so strong infrared radiation is formed on the water surface, which is consistent with the infrared measurement results shown in Fig. 6 (a).

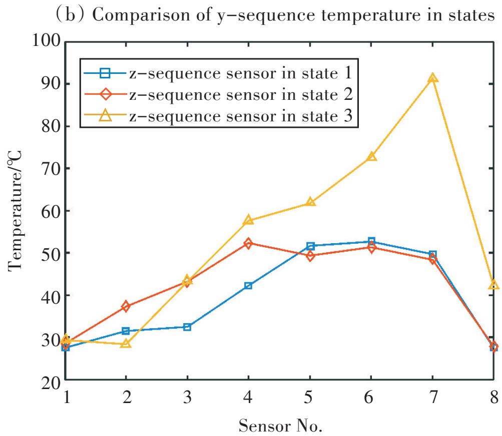
Fig. 8 shows that regardless of the discharge mode, the high temperature is obvious in the local area, mainly concentrated in the front section, while the temperature in the rear section has little difference from the environmental water temperature due to the mixing of water flow and the small emission. For the complex underwater measurement environment where there is not only water but also high-tem-



(a) Comparison of x−sequence temperature in states 1−3



(b) Comparison of y−sequence temperature in states 1−3



(c) Comparison of z−sequence temperature in states 1−3

Fig.8 Temperature diagram of temperature sensor

perature gas, the measurement data of the temperature sensors fluctuate. Although the data shown in Fig. 8 are not particularly accurate, qualitative analysis can still be carried out on the infrared suppression measures, namely that compared with the direct emission method of underwater exhaust gas, the two−stage cooling exhaust measures can significantly reduce the infrared local radiation on the water surface.

5 Conclusions

In this paper, the feasibility of two−stage cooling is verified by simulation, and the test parameters are determined. Through contrast test, it is found that the infrared radiation brightness in the water tank can be reduced by about 90% after the addition of the infrared suppression device, which fully verifies the effectiveness of the infrared suppression device. After the installation of the infrared suppression device on the exhaust pipe, it is found that the change of the back pressure of the diesel engine is small, indicating that if the design of the small−hole exhaust device is reasonable, the influence of the cooling system on the back pressure of the diesel engine will be small. However, the design of small−hole exhaust device also has the disadvantage that most of the high−temperature gas will escape through the front section of the small hole device and little gas will escape through the rear section of the device. In order to make full use of the space of the small holes, an optimized design of exhaust gas uniformity of the small−hole exhaust device will be added in the subsequent small hole design. The infrared suppression method has good reference significance for infrared suppression of underwater high−temperature exhaust gas of other equipment.

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两级双转子对置式离心压气机气动设计和强度校核

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摘　要:[**目的**]为完成某小型燃气轮机用两级双转子对置式离心压气机设计,[**方法**]将Concepts NREC和Numeca软件相结合,对两级双转子对置式离心压气机气动设计和三维流场进行校核;叶轮选取0Cr17Ni4Cu4Nb材料,采用ANSYS软件在线弹性范围内分析及校核离心叶轮强度和振动特性。[**结果**]气动设计结果表明,在设计流量点,两级离心压气机总压比为7.97,绝热效率为80.39%,稳定裕度为17.2%。强度和振动分析结果表明,叶轮静强度满足材料强度要求;根据“三重点”共振理论,两级离心叶轮均无共振危险。[**结论**]得到了同时满足气动、强度和振动要求的高压比、高效率和宽稳定裕度两级离心压气机设计方案,可为小型燃气轮机设计和技术集成、试验测试等提供基础支撑。

关键词:两级离心压气机;气动设计;强度校核;数值模拟

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柴油机水下排气红外抑制仿真及试验研究

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摘　要:[**目的**]为降低通气管航态下的潜艇红外尾迹,[**方法**]针对柴油机水下排气系统,提出一种能够抑制水下高温废气红外辐射的两级冷却方法,然后基于有限元流体分析方法分析红外抑制前、后的水面温度场。最后,基于仿真得到的初步数据搭建水下排气试验平台,并对红外抑制前、后的水面红外辐射亮度及水下温度进行测试。[**结果**]结果表明:两级降温措施对柴油机的高温排气有着良好的红外抑制效果,水面最大红外亮度可降低约90%。[**结论**]该方法对潜艇的隐蔽性改进具有较好的工程应用价值和军事价值。

关键词:柴油机;水下排气;红外抑制;试验